PHASE A EFFORT FINAL REPORT

FOR

FEASIBILITY STUDY OF A PRESSURE-FED ENGINE FOR A WATER RECOVERABLE SPACE SHUTTLE BOOSTER

Volume I - Executive Summary

Prepared For

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama

Contract NAS 8-28217

18 January 1972

AEROJET LIQUID ROCKET COMPANY
A DIVISION OF AEROJET-GENERAL
SACRAMENTO, CALIFORNIA

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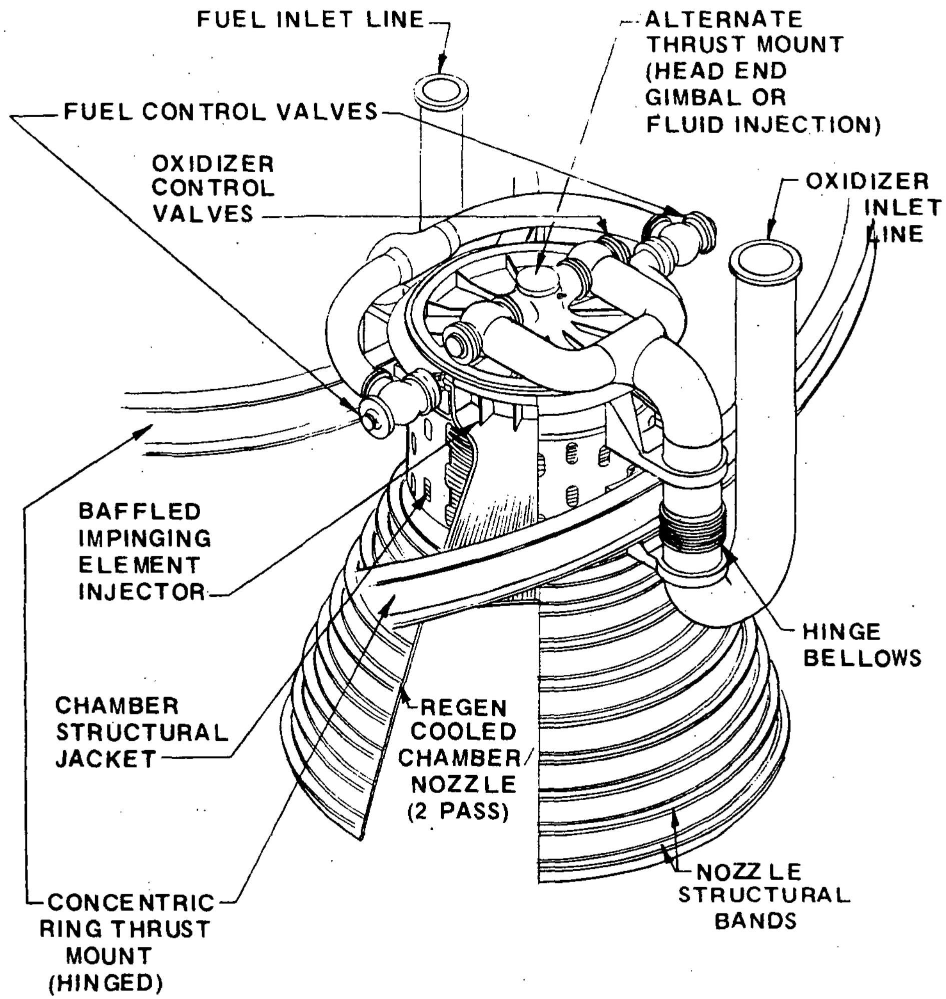
DATA REQUIREMENTS LIST

MSFC DATA PROCUREMENT DOCUMENT NO. 303

DATA REQUIREMENT MA-04

PRESSURE-FED BOOSTER ENGINE



OPERATING CONDITIONS

- PROPELLANT – LOX/RP-1
- THRUST – 1,200,000 LBS
- CHAMBER PRESSURE – 250 PSIA
- MIXTURE RATIO – 2.6:1
- EXPANSION RATIO – 6:1

FEATURES

- DEMONSTRATED LOX/RP-1 INJECTION
- DEVELOPED REGEN CHAMBER COOLING
- INJECTOR SHEET STOCK FAB.
  - LOW UNIT COST
  - SHORT DEVEL. LEAD TIME
- INJECTOR ELEMENT
  - FABRICATION
  - ELEMENT OPTIMIZATION
- REENTRY IMPACT SURVIVABILITY

FOREWORD

This Final Report on the Phase A Level effort for a feasibility study of a Pressure-Fed Booster engine has been prepared for the NASA-Marshall Space Flight Center. Design and system considerations have provided an engine concept selection for further preliminary design and program evaluation during the Phase B level of the study. This data has been prepared in compliance with Data Requirement MA-04 of the Contract NAS 8-28217 for a Feasibility Study of a Pressure-Fed Engine for a Water Recoverable Space Shuttle Booster.

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I. INTRODUCTION

The proposed ocean recoverable Pressure-Fed Booster for the Space Shuttle Vehicle provides a concept that has inherent reliability advantages when compared with other recoverable vehicle concepts. The NASA has contracted with vehicle airframe contractors and propulsion contractors to evaluate the feasibility of the Pressure-Fed Booster such that early decisions can be reached prior to initiation of the Space Shuttle Vehicle Phase C/D procurement. Aerojet Liquid Rocket Company (ALRC) was awarded contract NAS 8-28217 by NASA-Marshall Space Flight Center to provide propulsion support to the vehicle study contracts and to evaluate the Pressure-Fed Engine at a Phase A/B level over a thirteen week period beginning 1 December 1971.

The Phase A level effort of the contract has been completed and this Final Report documents the results. The Phase A level effort has provided a tentative concept selection for a Pressure-Fed Engine and propulsion support for the vehicle contractors. The Phase A effort evaluated multiple engine design concepts through parallel engine major component and system analyses.

The report has been presented in two parts in compliance with the Data Requirement MA-04. Volume I contains the Executive Summary and Volume II provides the Technical description.

II. ACTIVITIES

The Phase A level effort of the contracted Phase A/B study to evaluate the feasibility of a Pressure-Fed Engine has been completed. This effort has been divided between the Task I - Booster Vehicle Coordination and the parallel PFE analysis tasks, Task II - Engine Major Component Analysis and Task III - Engine System Analysis.

A. TASK I - BOOSTER VEHICLE COORDINATION

The purposes of Booster Vehicle coordination task are to: (1) determine engine requirements based on vehicle contractor and NASA input, and (2) provide an interface to assure free and rapid data exchange between ALRC and the vehicle contractors. The vehicle contractors have been under contract to evaluate the Pressure-Fed Booster before the award of the parallel propulsion contracts and have conducted significant analyses of the propulsion/ vehicle interfaces. Therefore, their prime interest has been directed toward resolution of particular design or program concerns.

Personnel have been organized to communicate directly with the vehicle contractors. Vehicle contractors questions are documented in an informal document titled "Vehicle Contractors Questions and Responses", which is maintained within the project to provide a record of the status of vehicle contractor questions. The ALRC baseline engine is described in the ALRC Pressure-Fed Booster Engine Interface Data book. Formal responses to Vehicle Contractor questions are by letter, TWX or Data Fax.

1. Revision 0 of the ALRC Pressure-Fed Booster Engine Interface Data book (Report 9755-71-3) has been issued.

2. Formal responses to Vehicle Contractors are maintained.

3. Current engine requirements based on discussions with vehicle contractors are tabulated and provided as a reference for the PFE design analysis.

4. Vehicle exchange ratios were obtained in discussions with vehicle contractors for use as weighted tradeoff factors in the selection of PFE design concepts.

B. PRESSURE-FED ENGINE CONCEPT TRADEOFFS

The first six weeks of the contract has provided for the design and system analyses of the Pressure-Fed Engine as shown by the Task II - Engine Major Component Analyses and Task III - Engine Systems Analyses activities shown in the task schedule in Figure II-1. An early definition of a Pressure-Fed Engine concept and program cost and schedule data was provided to NASA-MSFC on 6 December 1971. This data was provided to assist in the evaluation of vehicle contractor supplied data.

The analyses conducted to define the best concept for a Pressure-Fed Engine was performed in agreement with the procedures identified in the Study Plan submitted to NASA on 6 December 1971 in compliance with Data Requirement MA-01, as shown in Figure II-2. These analyses included preliminary concept screening of the major components, design analyses and tradeoffs of the remaining candidate concepts, and evaluation of the system impact of each approach. The major component screening charts showing all concepts considered are shown in Figures II-3 through II-7. Detailed tradeoffs were conducted for the engine major characteristics to determine the impact on vehicle gross liftoff weight. This served as a relative performance index for the engine characteristics.

Engine performance models, physical characteristics data, and steady state flow models were computerized for the different concepts and propellants under consideration. This capability was used to assist the design tradeoffs for the different concepts as well as assist in the data evaluation for the Task I - Vehicle Contractor Coordination.

PRESSURE-FED ENGINE STUDY TASK SCHEDULE

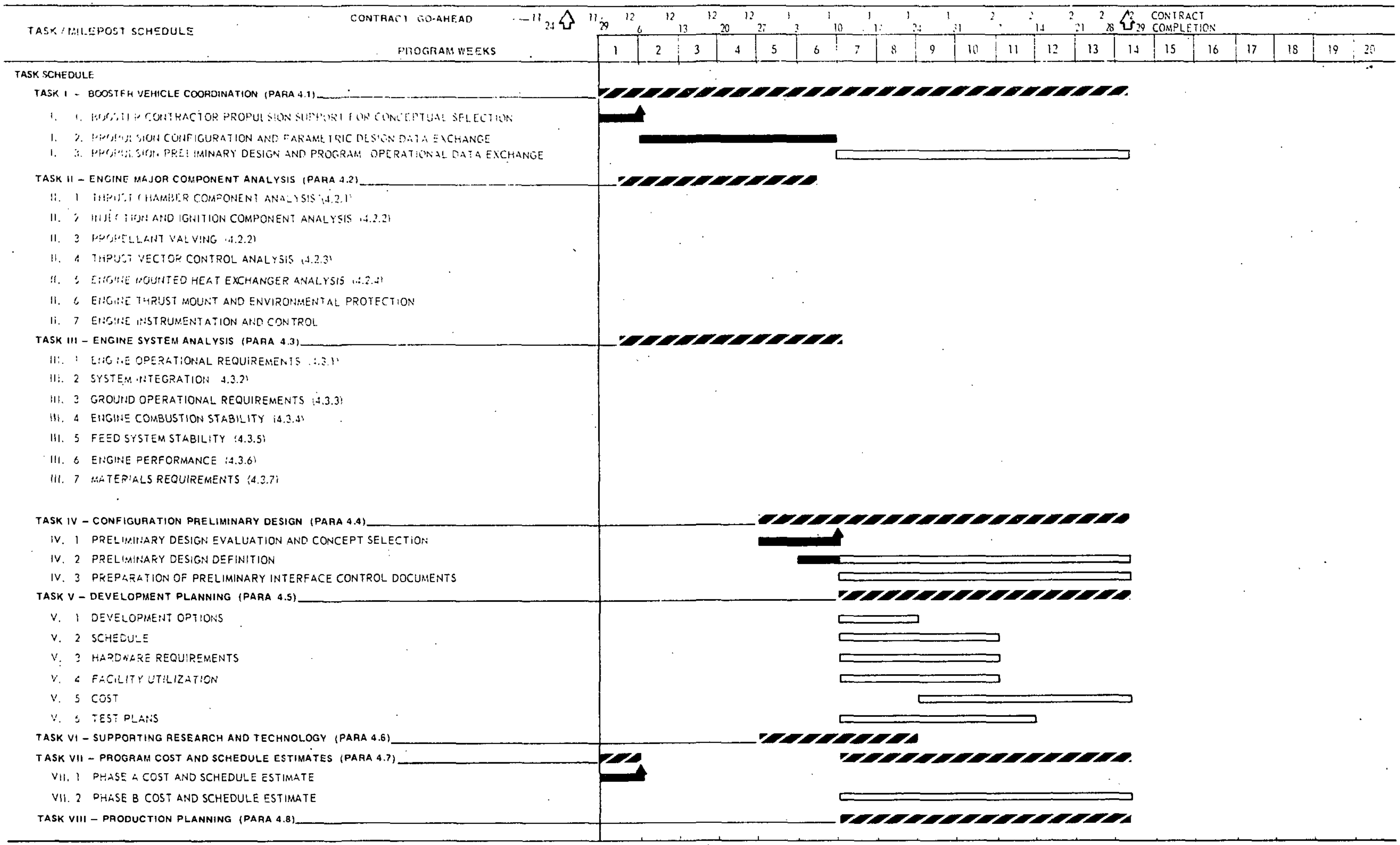

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Figure II-1

PFE STUDY MILEPOSTS AND DATA REQUIREMENTS SCHEDULE

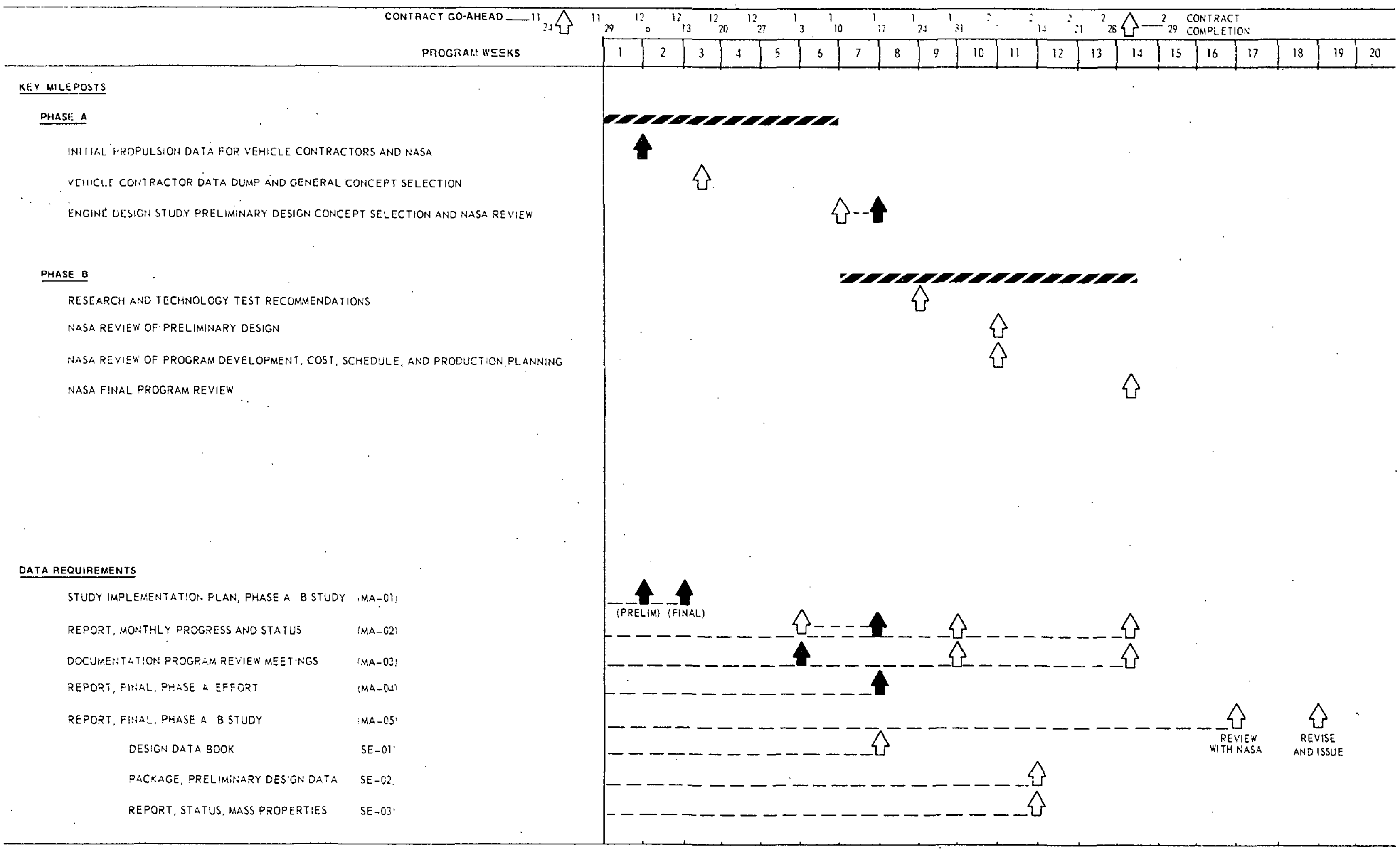

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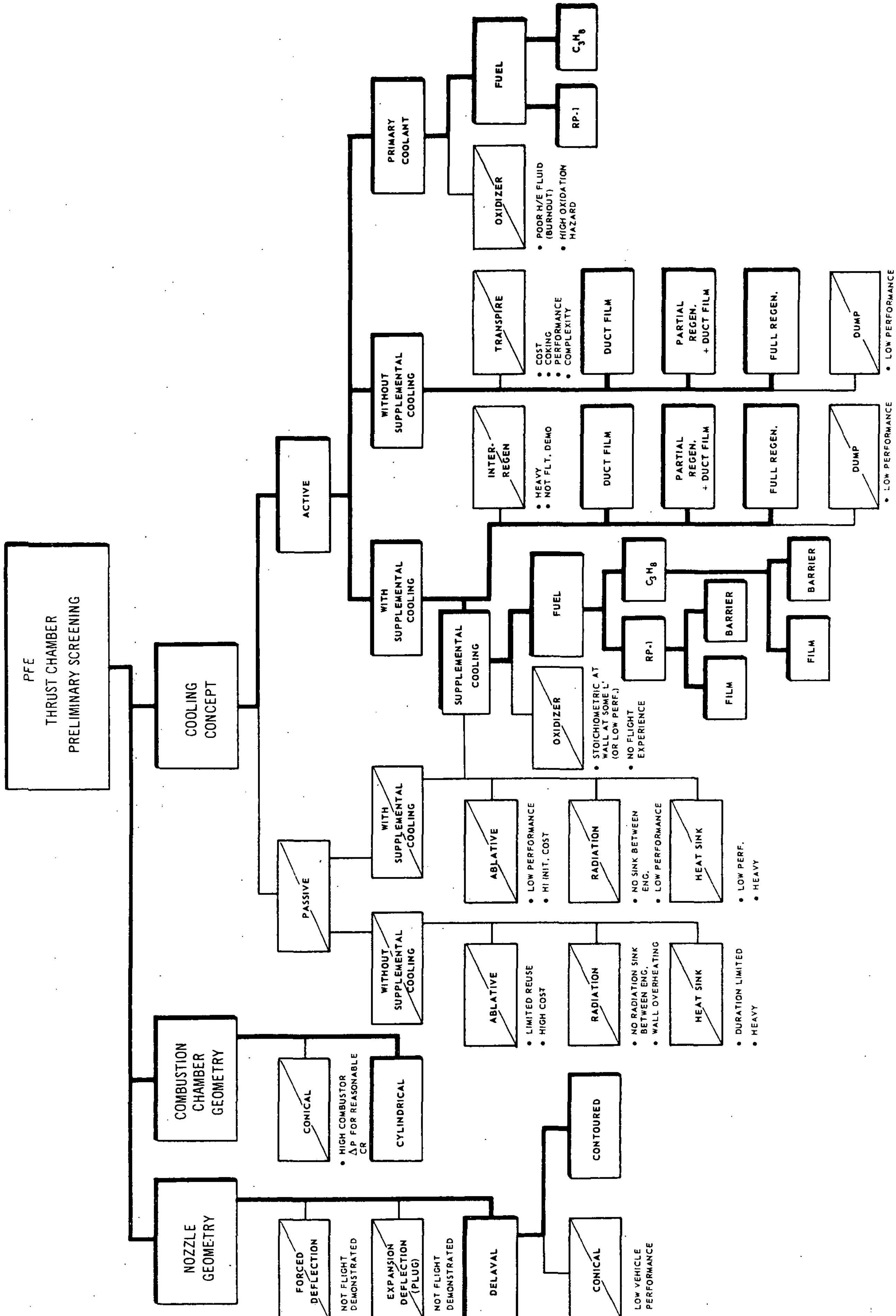
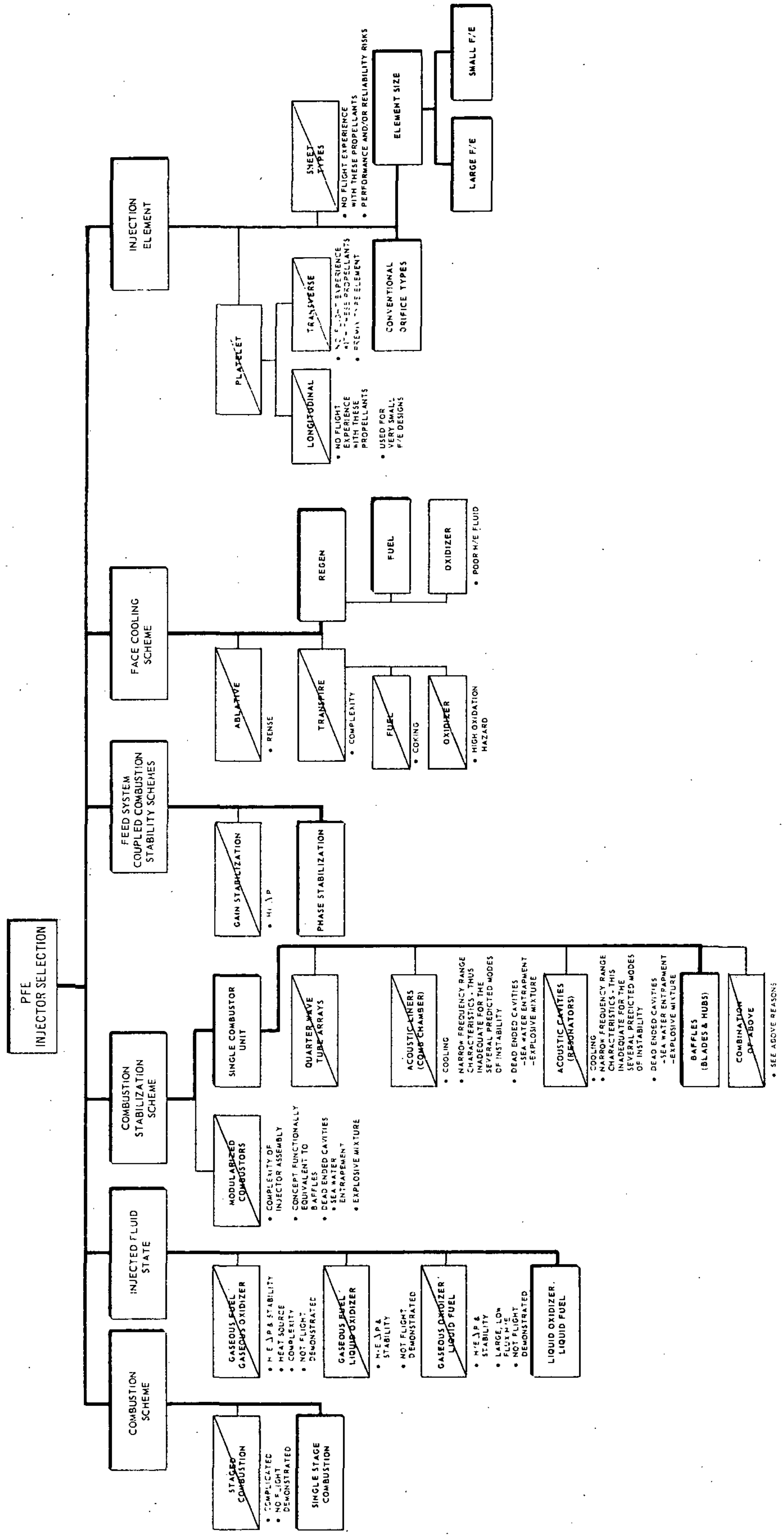
Figure II-2



PFE
THRUST CHAMBER
PRELIMINARY SCREENING
COOLING CONCEPT
COMBUSTION CHAMBER GEOMETRY
NOZZLE GEOMETRY
ACTIVE
PASSIVE
PRIMARY COOLANT
WITHOUT SUPPLEMENTAL COOLING
WITH SUPPLEMENTAL COOLING
FUEL
OXIDIZER
• POOR H/E FLUID (BURNOUT)
• HIGH OXIDATION HAZARD
RP-1
C_3H_8
TRANSPIRE
• COST
• COKING
• PERFORMANCE
• COMPLEXITY
DUCT FILM
PARTIAL REGEN. + DUCT FILM
FULL REGEN.
DUMP
• LOW PERFORMANCE
INTER-REGEN
• HEAVY
• NOT FLT. DEMO
SUPPLEMENTAL COOLING
• STOICHIOMETRIC AT WALL AT SOME L' (OR LOW PERF.)
• NO FLIGHT EXPERIENCE
BARRIER
FILM
ABLATIVE
• LOW PERFORMANCE
• HI INIT. COST
RADIATION
• NO SINK BETWEEN ENG.
• LOW PERFORMANCE
HEAT SINK
• LOW PERF.
• HEAVY
• LIMITED REUSE
• HIGH COST
• NO RADIATION SINK BETWEEN ENG.
• WALL OVERHEATING
• DURATION LIMITED
• HEAVY
CONICAL
• HIGH COMBUSTOR ΔP FOR REASONABLE CR
CYLINDRICAL
FORCED DEFLECTION
• NOT FLIGHT DEMONSTRATED
EXPANSION DEFLECTION (PLUG)
DELAVAL
CONTOURED
• LOW VEHICLE PERFORMANCE

Figure II-3



PFE Injector Selection

Figure II-4

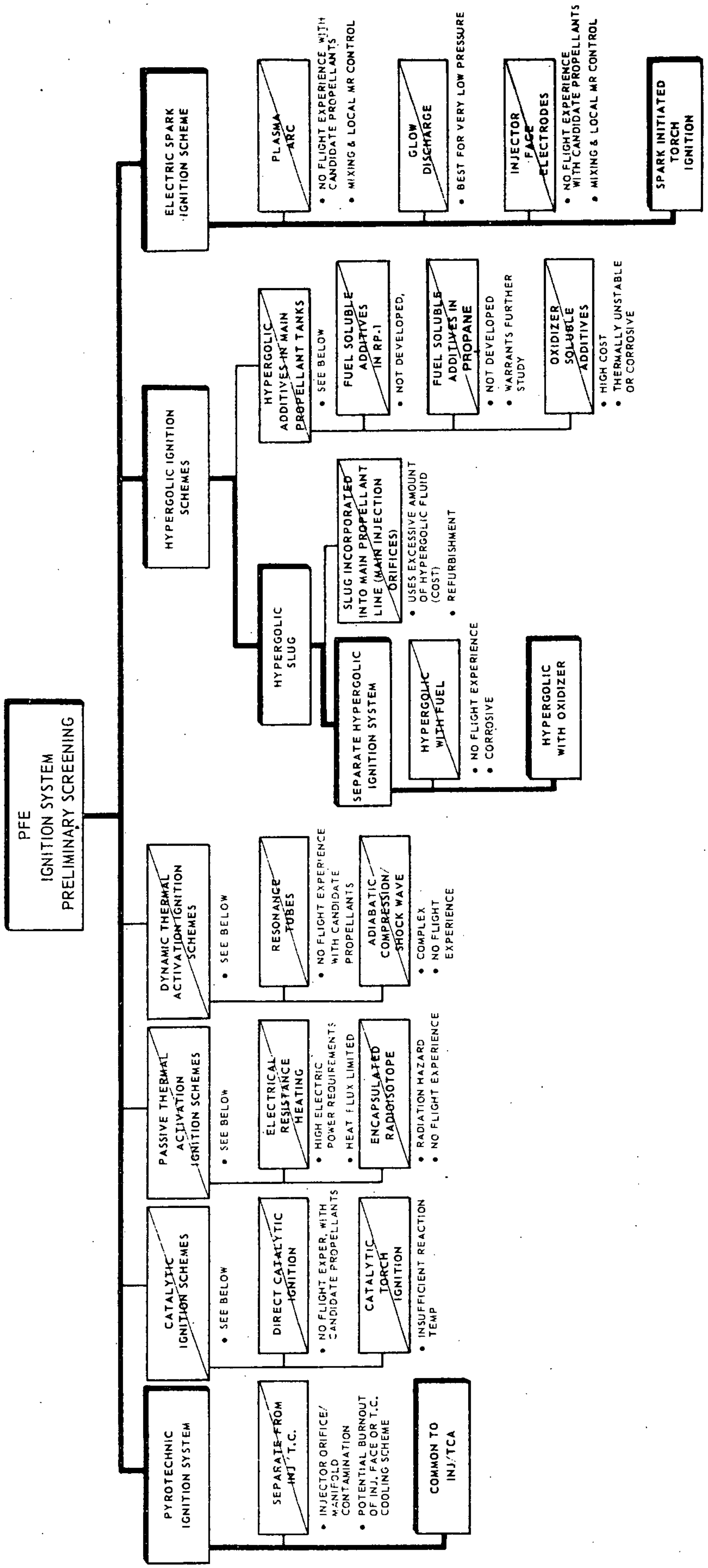
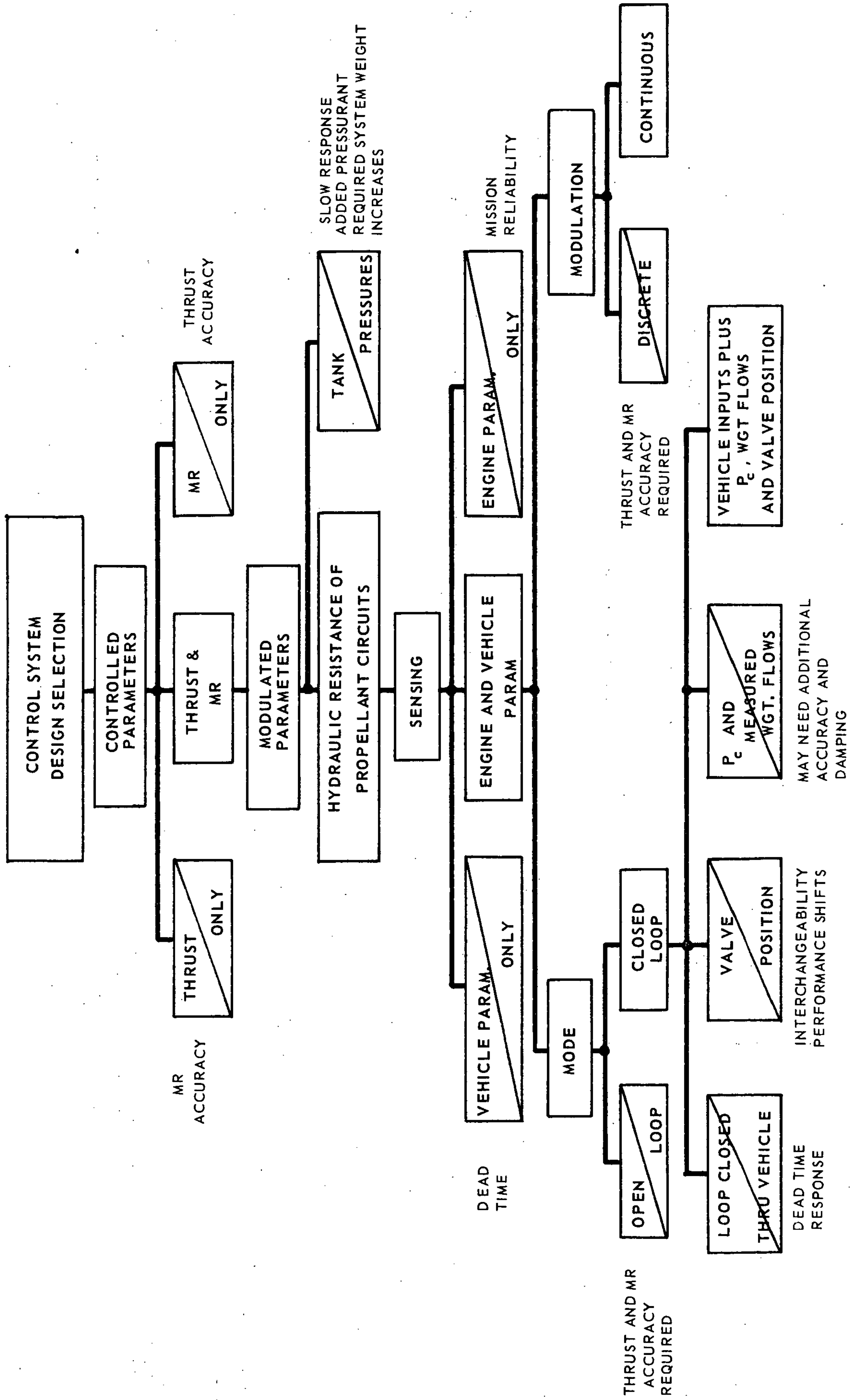

PFE
IGNITION SYSTEM
PRELIMINARY SCREENING
PYROTECHNIC IGNITION SYSTEM
SEPARATE FROM INJ./T.C.
• INJECTOR ORIFICE/MANIFOLD CONTAMINATION
• POTENTIAL BURNOUT OF INJ. FACE OR T.C. COOLING SCHEME
COMMON TO INJ./TCA
CATALYTIC IGNITION SCHEMES
• SEE BELOW
DIRECT CATALYTIC IGNITION
• NO FLIGHT EXPER. WITH CANDIDATE PROPELLANTS
CATALYTIC TORCH IGNITION
• INSUFFICIENT REACTION TEMP
PASSIVE THERMAL ACTIVATION IGNITION SCHEMES
• SEE BELOW
ELECTRICAL RESISTANCE HEATING
• HIGH ELECTRIC POWER REQUIREMENTS
• HEAT FLUX LIMITED
ENCAPSULATED RADIOISOTOPE
• RADIATION HAZARD
• NO FLIGHT EXPERIENCE
DYNAMIC THERMAL ACTIVATION IGNITION SCHEMES
• SEE BELOW
RESONANCE TUBES
• NO FLIGHT EXPERIENCE WITH CANDIDATE PROPELLANTS
ADIABATIC COMPRESSION/SHOCK WAVE
• COMPLEX
• NO FLIGHT EXPERIENCE
HYPERGOLIC IGNITION SCHEMES
HYPERGOLIC SLUG
SLUG INCORPORATED INTO MAIN PROPELLANT LINE (MAIN INJECTION ORIFICES)
• USES EXCESSIVE AMOUNT OF HYPERGOLIC FLUID (COST)
• REFURBISHMENT
SEPARATE HYPERGOLIC IGNITION SYSTEM
HYPERGOLIC WITH FUEL
• NO FLIGHT EXPERIENCE
• CORROSIVE
HYPERGOLIC WITH OXIDIZER
HYPERGOLIC ADDITIVES IN MAIN PROPELLANT TANKS
• SEE BELOW
FUEL SOLUBLE ADDITIVES IN RP-1
• NOT DEVELOPED,
FUEL SOLUBLE ADDITIVES IN PROPANE
• NOT DEVELOPED
• WARRANTS FURTHER STUDY
OXIDIZER SOLUBLE ADDITIVES
• HIGH COST
• THERMALLY UNSTABLE OR CORROSIVE
ELECTRIC SPARK IGNITION SCHEME
PLASMA ARC
• NO FLIGHT EXPERIENCE WITH CANDIDATE PROPELLANTS
• MIXING & LOCAL MR CONTROL
GLOW DISCHARGE
• BEST FOR VERY LOW PRESSURE
INJECTOR FACE ELECTRODES
• NO FLIGHT EXPERIENCE WITH CANDIDATE PROPELLANTS
• MIXING & LOCAL MR CONTROL
SPARK INITIATED TORCH IGNITION

Figure II-5



CONTROL SYSTEM DESIGN SELECTION
CONTROLLED PARAMETERS
THRUST ONLY
MR ACCURACY
THRUST & MR
MR ONLY
THRUST ACCURACY
MODULATED PARAMETERS
HYDRAULIC RESISTANCE OF PROPELLANT CIRCUITS
TANK PRESSURES
SLOW RESPONSE
ADDED PRESSURANT
REQUIRED SYSTEM WEIGHT
INCREASES
SENSING
VEHICLE PARAM. ONLY
DEAD TIME
ENGINE AND VEHICLE PARAM
ENGINE PARAM. ONLY
MISSION RELIABILITY
MODE
OPEN LOOP
THRUST AND MR ACCURACY REQUIRED
CLOSED LOOP
MODULATION
DISCRETE
THRUST AND MR ACCURACY REQUIRED
CONTINUOUS
LOOP CLOSED THRU VEHICLE
DEAD TIME RESPONSE
VALVE POSITION
INTERCHANGEABILITY PERFORMANCE SHIFTS
P_c AND MEASURED WGT. FLOWS
MAY NEED ADDITIONAL ACCURACY AND DAMPING
VEHICLE INPUTS PLUS P_c, WGT FLOWS AND VALVE POSITION

Figure II-6

THRUST VECTOR CONTROL SYSTEM SELECTION MATRIX

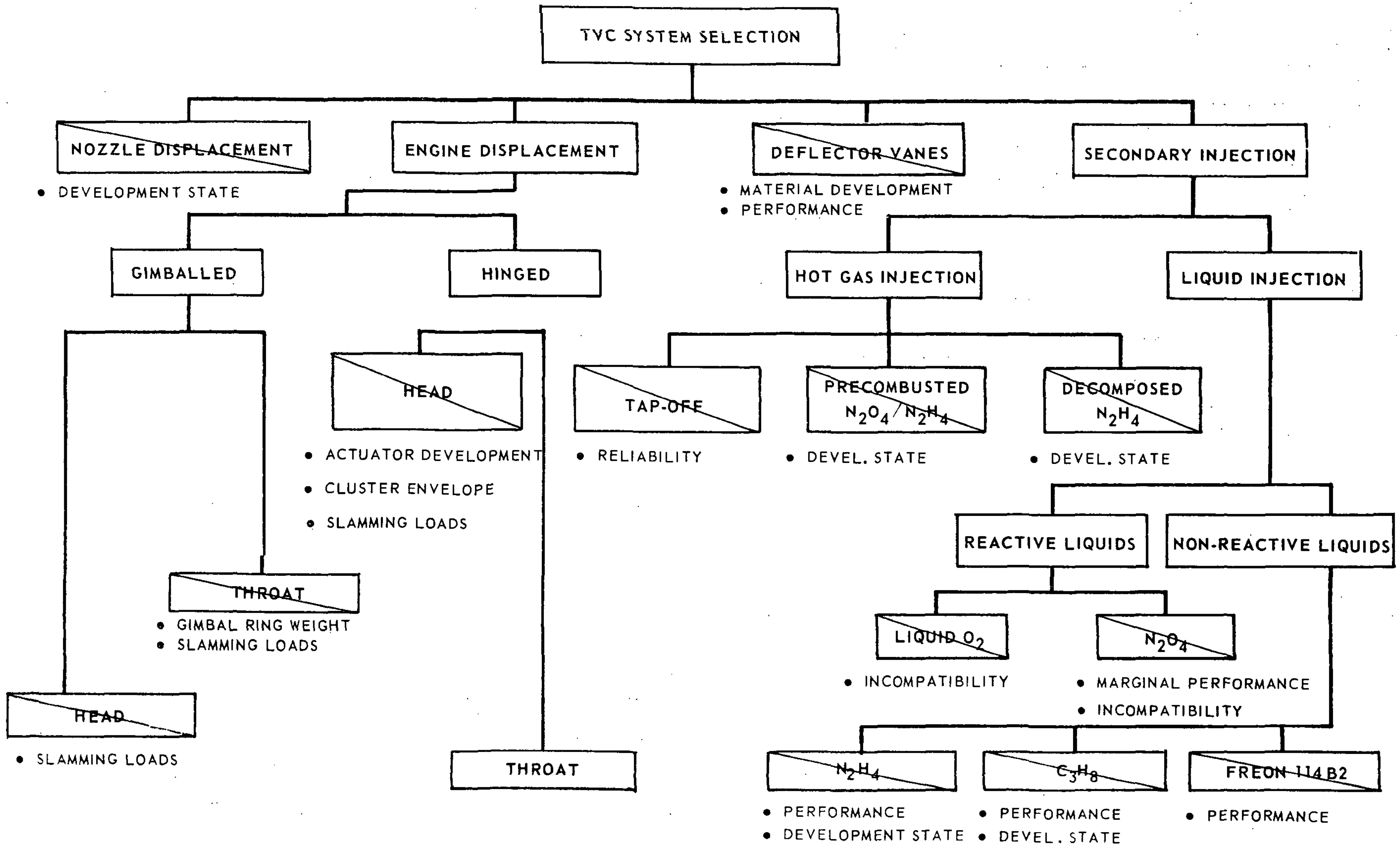


Figure II-7

III. CONCEPT SELECTION

A primary consideration was the evaluation of the propellant combination to be baselined for the PFE design concept. Both LOX/RP-1 and LOX/Propane were evaluated from an engine performance and thrust chamber cooling standpoint. In addition, the propellant handling and facility considerations were evaluated. Based on this review, LOX/RP-1 were selected for baseline consideration in view of the known injection, combustion, and cooling capabilities with the RP-1. Figure III-1 summarizes the advantages and disadvantages of each propellant combination.

The engine concept identified as baseline for further evaluation in the Phase B level of the contract is shown in Figure III-2. The engine has a regeneratively cooled combustion chamber and nozzle in conjunction with an impinging element injector. The injector is designed to be fabricated using predominately sheet stock materials with the impinging elements fabricated separately and then installed into the injector face. Combustion stabilizing baffles are used to assure dynamic combustion stability. The baffles are fabricated with internal coolant flow which injects at the tip. The coolant is shown to be oxidizer in the injector design shown in Figure III-3; however, this will be evaluated further in Phase B.

The engine has two oxidizer valves and two fuel valves to provide better distribution of the propellant into the injector and regeneratively cooled chamber, and to provide better valve sealing characteristics by minimizing valve seat diameter. The valves are hydraulically actuated with high pressure RP-1 obtained from a small engine mounted pump.

The combustion chamber is shown as a two-pass regenerative jacket with the fuel entering at the head-end, Figure III-4. The study considered head-end gimbaling, fluid injection, and hinged at the center of gravity for thrust vector control. The TVC concept shown in Figure III-2 is a C.G. hinged

approach to allow better restraint of the engine assembly during the significant transverse acceleration loads projected for ocean impact by the vehicle studies. The moments generated by the cantilevered engine would be excessive for a head-end gimbaled engine. In addition, the hinged approach allows the use of the Saturn SIC vehicle gimbal actuator.

The selected method of ignition utilizes a hypergolic cartridge containing a mixture of TEA and TEB which is hypergolic with liquid oxygen. This method provides for reliable, flight proven ignition while minimizing weight and cost.

A closed loop control system utilizing a small engine mounted controller was selected to provide thrust and mixture ratio control by modulating the propellant valves. This small controller can be used to provide self checkout, self start, and self shutdown capability upon command from the vehicle.

PRESSURE-FED ENGINE

- **PROPELLANT CONSIDERATIONS – RP vs PROPANE**

	RP	PROPANE
• **ADVANTAGES**	• EXTENSIVE ENGINE DEVELOPMENT AND FLIGHT EXPERIENCE • PERFORMANCE CHARACTERIZED • INJECTOR MIXING CHARACTERIZED • DEMONSTRATED HEAT TRANSFER • CHARACTERIZED REUSE CAPABILITY – HOT GAS SIDE COKING – FUEL SIDE FILM BUILDUP – CLEANING • HIGHER DENSITY AT AMBIENT • EASIER FACILITY HANDLING	• HIGHER POTENTIAL PERFORMANCE – I_s • AMBIENT VAPORIZATION – RESIDUAL ENGINE PROPELLANTS – ECOLOGY CONSIDERATIONS • CONSTANT DENSITY AT AMBIENT PRESSURE
• **DISADVANTAGES**	• LOWER THEORETICAL PERF. – I_s • LOW VAPOR PRESSURE – RESIDUAL ENGINE PROPELLANTS – ECOLOGY CONSIDERATIONS • DENSITY VARIATION WITH AMBIENT TEMPERATURE	• NO DEVEL. OR FLIGHT EXPERIENCE • DELIVERED PERF. UNCERTAINTY – ENERGY RELEASE EFF. – CHAMBER COOLING REQM'TS • UNCERTAIN COOLING CAPABILITY – HEAT TRANSFER COEFF. – FILM BOILING – REGEN. ΔP REQ'MTS • LOWER DENSITY AT AMBIENT • HANDLING/PROPELLANT LOSSES • COKING AND FILM BUILDUP UNCERTAINTY

- **SUMMARY**
  - BOTH PROPELLANTS ARE VIABLE FUELS
  - COST AND EXHAUST PRODUCT TOXICITY SIMILAR
  - RP IS A BETTER CHARACTERIZED PROPELLANT
    - REDUCES DEVELOPMENT RISK AND FLIGHT UNCERTAINTIES
    - HIGHER CONFIDENCE IN FLIGHT PERFORMANCE PREDICTABILITY

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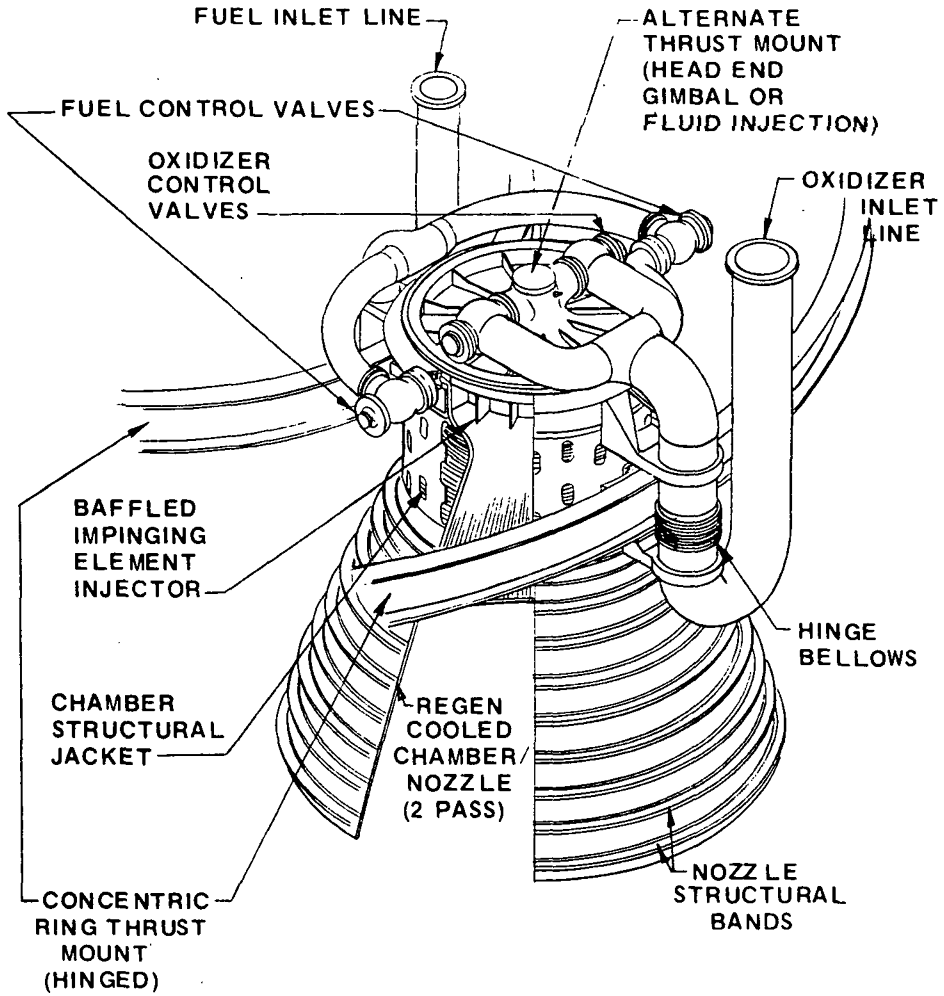
Figure III-1

PRESSURE-FED BOOSTER ENGINE



OPERATING CONDITIONS

- PROPELLANT – LOX/RP-1
- THRUST – 1,200,000 LBS
- CHAMBER PRESSURE – 250 PSIA
- MIXTURE RATIO – 2.6:1
- EXPANSION RATIO – 6:1

FEATURES

- DEMONSTRATED LOX RP-1 INJECTION
- DEVELOPED REGEN CHAMBER COOLING
- INJECTOR SHEET STOCK FAB.
  - LOW UNIT COST
  - SHORT DEVEL. LEAD TIME
- INJECTOR ELEMENT
  - FABRICATION
  - ELEMENT OPTIMIZATION
- REENTRY IMPACT SURVIVABILITY

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Figure III-2

IV. TECHNOLOGY/DEVELOPMENT PHASE

One of the objectives during the Phase A study was to identify problem areas associated with the selected engine concepts. These problem areas then became the basis for recommended technology programs which are presented in Table IV-1.

Water recovery of the booster exposes the engines including internal manifolding to contamination from both the minerals and sea life that exists in the water. This and the requirement to reuse the engines in subsequent launches established the requirement for materials compatibility and cleaning technology programs.

Propane offers a performance advantage over RP-1 if the propellant can be used in a film boiling heat transfer mode for regenerative cooling of the thrust chamber. Since this type of data is not available for the coolant velocity and heat fluxes experienced in this engine, a technology program to obtain film boiling data was recommended. In addition, further information is required on the phase change characteristics of propane for duct cooling studies and the rate of material buildup on the inside of the regenerative tubes due to propellant cracking for both RP-1 and propane.

A thorough evaluation of propane and RP-1 cannot be completed until more data is obtained on the mixing and combustion characteristics of propane with liquid oxygen. This includes the effect of injection element type since RP-1 and propane are significantly different in fluid properties.

Vehicle contractors in general favor a fixed engine with fluid injection into the nozzle for thrust vector control since the structural weight and boattail dimensions of the booster are significantly reduced over a gimbaled engine. However, performance degradation due to the injected fluid can easily cost the vehicle more in weight penalty than was saved with the

light weight structure. To properly compare the two methods of thrust vector control, it is necessary to obtain further liquid injection performance data.

The large thrust level and vehicle sensitivity to low pressure drop results in valve diameters and sealing loads that are beyond state-of-the-art technology. Since this is a major component in the pressure fed system, data on seal loading and cyclic life is required.

One method of obtaining thrust vector control involves hinging the engine in one plane versus the normal two plane gimbal. This enables the propellant inlet lines from the vehicle to interface with the engine through a swivel seal which eliminates the requirements for large diameter articulating bellows and results in a significant weight savings. This swivel seal is larger in diameter than those utilized on past engine programs and, therefore, requires a technology program to verify seal life capability.

Feed system coupling is a problem involved in any vehicle design. To provide for proper control of this situation, a detailed system stability analysis is required to establish proper stability margins and design criteria.

The most severe loads (up to 25 g's) imposed on the engine occur during water reentry slap down. Since the weight of the chamber and nozzle is largely a function of the loading, a detailed dynamic load analysis of water reentry is recommended as a technology program to ensure that engine weight is maintained at a minimum.

Vehicle contractor studies have indicated that a monopropellant N_2H_4 gas generator provides an efficient method of tank pressurization. In addition, the N_2H_4 exhaust would be used to power hydraulic pumps on the engine

which are needed for gimbal actuator power. Due to the large flow rate required, state-of-the-art technology does not exist for this size gas generator and, therefore, warrants a technology program.

TABLE IV-I

PRESSURE-FED ENGINE TECHNOLOGY / DEVELOPMENT AREAS

TECHNOLOGY/DEVELOPMENT AREAS	AREAS TO BE DEMONSTRATED	METHOD
• THRUST CHAMBER/INJECTOR OPERATIONAL REUSE	• MATERIALS SALT WATER COMPATIBILITY	• COMPONENT ELEMENTS AND MATERIALS TESTING. • INVESTIGATION INTO MARINE BIOLOGY COMPATIBILITY.
	• INJECTOR/CHAMBER CLEANING	• CLEANING EVALUATION AND DEMO. OF TYPICAL FLOW PASSAGES. • REPRESENTATIVE INJECTOR/REGEN. CHAMBER SEA IMMERSION, CLEANING AND TEST CHECKOUT.
• FUEL COOLANT CAPABILITIES	• PROPANE HEAT TRANSFER CHARACTERISTICS TO DESIGN HEAT FLUX RANGE.	• CONTROLLED HEATED TUBE THERMO. DATA FOR FILM BOILING HEAT TRANSFER COEFFICIENT EXTENSION.
	• MATERIAL DEPOSITS ON INTERNAL TUBE WALL DUE TO PROPELLANT CRACKING - RP-1 AND PROPANE.	• EXTENDED DURATION CONTROLLED EXPERIMENT WITH HEATED TUBE.
	• PROPANE DUCTED-FILM COOLANT PHASE CHANGE.	• CONTROLLED HEATED DUCT CHANNEL FOR THERMODYNAMIC EVALUATION.

PRESSURE-FED
ENGINE TECHNOLOGY / DEVELOPMENT AREAS (CONT.)

TECHNOLOGY/DEVELOPMENT AREAS	AREAS TO BE DEMONSTRATED	METHOD
o INJECTOR ELEMENT OPTIMIZATION	o LOX/PROPANE INJECTION ELEMENT MIXING CHARACTERISTICS	o SUBSCALE ELEMENT FLOW TESTS AND FIRING EVALUATION - PERFORMANCE OPTIMIZATION - INJECTOR/CHAMBER COMPATIBILITY
o FLUID INJECTION THRUST VECTOR CONTROL	o REACTED PROPELLANT AND GASEOUS FLUID INJECTION PERFORMANCE	o EVALUATE GITVC PERFORMANCE IN REPRESENTATIVE ENGINE TESTING - GASEOUS He - REACTED LOX/RP-1 OR PROPANE - DECOMPOSED N_2H_4
o PROPELLANT VALVE SEALING AND LIFE	o LARGE DIAMETER LOADS AND CYCLIC LIFE	o VALVE SEAL ANALYSIS AND TESTING IN SIMULATED VALVE
o GIMBAL SWIVEL SEALING	o LARGE DIAMETER SLIDING SEAL MATERIALS AND DESIGN CRITERIA	o SEAL LIFE ANALYSIS AND TEST SIMULATION
o FEED SYSTEM COUPLING STABILITY	o FEED SYSTEM STABILITY MARGINS AND DESIGN CRITERIA	o DETAILED DYNAMIC ANALYSIS OF ENGINE AND FEED SYSTEM FOR STABILITY MARGINS OVER THROTTLE RANGE. - GAIN STABILIZED - PHASE STABILIZED

PRESSURE-FED
ENGINE TECHNOLOGY / DEVELOPMENT AREAS (CONT.)

TECHNOLOGY/DEVELOPMENT AREAS	AREAS TO BE DEMONSTRATED	METHOD
o RECOVERY DYNAMIC LOAD ANALYSIS	o IMPOSED DYNAMIC LOADS DURING WATER REENTRY	o DETAILED DYNAMIC LOAD ANALYSIS TO DETERMINE IMPOSED LOADS AND STRUCTURAL DESIGN REQUIREMENTS.
o MONOPROPELLANT N_2H_4 GAS GENERATOR FOR PRESSURIZATION	o HIGH FLOWRATE MONOPROPELLANT GAS GENERATOR	o TEST DEMONSTRATION OF SECTION OF FULL SCALE GENERATOR TO DETERMINE - LOW COST CATALYST - CATALYST LIFE o FULL SCALE GAS GENERATOR DEMONSTRATION.

V. PROGRAM PLANNING

The objective of the Phase A study was to provide a selected engine concept that would best meet the shuttle vehicle booster requirements. To accomplish this objective, it was necessary that critical vehicle data on general concept selection be available by the midpoint of Phase A as shown in Figure II-2. Since this data is still not available on some of the vehicles, it was necessary to postpone some of the concept selections. The major concept selections that are still in question include injector element type, method of thrust vector control, combustion chamber geometry, type of cooling geometry (two pass, single pass, etc.), and type of baffle coolant (fuel vs oxidizer).

The first activity accomplished in Phase B will be the reevaluation of the engine based on consistent vehicle exchange ratios as determined by NASA. This will enable all the concepts to be selected for the engine. The study will then conduct a preliminary design of the selected engine concept as originally proposed for Phase B. To insure that proper vehicle considerations continue to be incorporated into the design, parallel support from the vehicle contractors is recommended during Phase B.